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Distribution and Environmental Suitability of the Smallscaled Rock Agama, *Paralaudakia microlepis* (Sauria: Agamidae) in the Iranian Plateau

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Abstract Predictive potential distribution modeling is of increasing importance in modern herpetological studies and determination of environmental and conservation priorities. In this article we provided results of analysis and forecasts of the potential distribution of smallscaled rock agama *Paralaudakia microlepis* (Blanford, 1874) using the distribution models through Maxent (www.cs.princeton.edu/ ~ schapire / maxent). We made an attempt for comparison of input of bioclimatic factors and characteristics of biotope distribution for three species of genus *Paralaudakia*. Constructed model identified dissemination of *Paralaudakia microlepis* enough performance (AUC = 0.972 with dispersion 0.003). According to the map constructed, the most suitable habitats of smallscaled rock agama *Paralaudakia microlepis* are located in southern and eastern Iran, the west of central Pakistan and southeastern Afghanistan.

Keywords Iranian Plateau, Agamidae, Potential species distribution modeling, *Paralaudakia microlepis*, Maxent modeling

1. Introduction

Species distribution modeling is a powerful tool to investigate important biological questions. It can allow predicting of lost biodiversity, identify areas with highest risk of biological invasions and thereby its conservation and identification of suitable areas for threatened species (Thuiller *et al.*, 2005; Ficetola *et al.*, 2010; Reshetnikov and Ficetola, 2011; Bernardes *et al.*, 2013). Predictive potential distribution modeling is of increasing importance in modern herpetological studies and determination of environmental priorities (Litvinchuk *et al.*, 2010; Doronin, 2012; Bernardes *et al.*, 2013; Ananjeva and Golynsky, 2013; Ficetola *et al.*, 2013; Hosseinian Yousefkhani *et al.*, 2013). It was shown that bioclimatic models are useful in predicting amphibians and reptile's distribution due to their ectothermy (Buckley *et al.*, 2012).

Using Maxent as the modeling technique and Asian rock agamas (genus *Paralaudakia* Baig, Wagner, Ananjeva and Böhme, 2012) as a model system we construct a bioclimatic model for the poorly known narrow spread species *Paralaudakia microlepis* (Blanford, 1874) and made an attempt to compare input of bioclimatic factors to distribution of different species (*P. caucasia*, *P. lehmanni*, *P. microlepis*) (Ananjeva and Golynsky, 2013; Hosseinian Yousefkhani *et al.*, 2013).

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We expect to provide an additional estimation of these agamas ecological niche, which can be used to predict its potential geographical distribution.

Recently, Baig *et al.* (2012) revision recognized within the genus *Laudakia* three genera: *Laudakia* Gray, 1845; *Stellagama* Baig, Wagner, Ananjeva and Böhme, 2012; and *Paralaudakia* Baig, Wagner, Ananjeva and Böhme, 2012. The latter is an agamid genus inhabiting the mountain rock landscapes. Its distribution ranges from Greece and the Nile River delta on the west, through the Middle East and Central Asia, to Gobi Altai on the northeast and Brahmaputra River on the east (Ananjeva and Tuniyev, 1994; Rastegar-Pouyani and Nilson, 2002; Ananjeva *et al.*, 2006). *P. microlepis* is poorly studied species of Asian rock agamids of *P. caucasia* complex with limited distribution within the Iranian Plateau (Anderson, 1968). We gathered all available data on the distribution of *P. microlepis* to describe its distribution range and use MAXENT model to identify suitable habitats in Iran, Afghanistan and Pakistan; its range was never been mapped and analyzed. The results of model will be of value for understanding of the biogeography of Asian rock agamas and determination of their conservation status.

In this study, we use maximum entropy modeling to study the distribution of *Paralaudakia microlepis* in the Middle East based on geographic distributional data and environmental predictor variables, with the following objectives: 1) to determine which environmental factors are correlated with the distribution of this species and another earlier studied species of this genus and 2) to compare potential areas by applying models based on those factors of rock agamas of the genus *Paralaudakia*.

2. Materials and Methods

We combined literature records, localities data on museum specimens from Iran, Afghanistan and Pakistan stored in Sabzevar University Herpetological Collection (SUHC), California Academy of Sciences (CAS), Pakistan Museum of Natural History (PMNH), Zoological Institute, Russian Academy of Sciences (ZISP), Zoological Museum, Moscow State University (ZMMGU), and data of the field surveys of authors and colleagues to describe the distribution of *Paralaudakia microlepis* through its entire range. We also used all the available literature records in Iran and Pakistan (Anderson, 1999; Macey *et al.*, 1998, 2000; Nazarov, Melnikov, pers. communications). The data (Table 1) were used to prepare a new updated distribution map for *P. microlepis*, and served as baseline to build a correlative species distribution model identifying the most suitable areas.

Maximum Entropy modeling (MAXENT) was used to assess the potential distribution of *Paralaudakia microlepis* in the Middle East and to made an attempt of comparison of characteristics of biotope distribution of three species of rock agamas of *Paralaudakia* (Ananjeva and Golynsky, 2013; Hosseinian Yousefkhani *et al.*, 2013). In the present work the records from 33 localities in Iran, Pakistan and Afghanistan were analyzed.

Maximum Entropy modeling (MAXENT) was used to assess the potential distribution of *Paralaudakia microlepis* in the Iranian Plateau. MAXENT combines distribution data with environmental factors and assesses the probability of presence of one species in a given cell on the basis of environmental features in that cell. This method is considered as one of the most important in modern herpetological studies and determination of environmental priorities. The model was fitted using linear, quadratic and hinge features.

We used data from 19 bioclimatic variables (Bio 1–19), the parameters obtained from the WorldClim database (http://www.worldclim.org/ current) and CliMond database (www.climond.org) with resolution of geospatial layers 10 acrsec, as well as the geographic coordinates of 33 known locations records collected in different periods. We considered seven bioclimatic variables that are normally expected to be important for metabolism and thermoregulation of reptiles, as well as their water availability. These variables included: 1) precipitation of warmest quarter (mm); 2) precipitation of coldest quarter (mm); 3) highest weekly radiation (W m^2); 4) temperature seasonality (C of V); 5) precipitation of driest week (mm); 6) radiation of driest quarter (W m^2); and 7) mean diurnal temperature range (mean.period max-min) (ºC). We follow some author's conclusions and did not include altitude because it is strongly correlated to temperature (Harris *et al.*, 2013; Hosseinian Yousefkhani *et al.*, 2013). In the model, we used accessibility (Nelson, 2008; Uchida and Nelson, 2010) as a measure of sampling bias and a logistic output, with MAXENT suitability ranging from zero (no suitability) to one (maximum suitability).

3. Results

We obtained records of *Paralaudakia microlepis* from 33 localities in the Iranian Plateau (Figure 1, Table 2). The distribution of *P. microlepis* includes the region in the southern, central and eastern parts of the Iranian Plateau within the territory of Iran; in the mountain regions of

Figure 1 Potential distribution modeling of *Paralaudakia microlepis* within the Iranian Plateau. Different colors in the map indicate different suitability values. White: 55%–37% suitability; Light-gray: 72%–55% suitability; Dark-gray: 100%–72% suitability. The distribution range of *Paralaudakia caucasia* is shown by white line.

Table 1 Bioclimatic variables used in Maxent modeling.

	Variables
BIO2	Mean diurnal temperature range
BIO3	Isothermality
BIO4	Temperature seasonality
BIO5	Max temperature of warmest week
BIO6	Min temperature of coldest week
BIO8	Mean temperature of wettest quarter
BIO9	Mean temperature of driest quarter
BIO12	Annual precipitation
BIO14	Precipitation of driest week
BIO15	Precipitation seasonality
BIO18	Precipitation of warmest quarter
BIO19	Precipitation of coldest quarter
BIO21	Highest weekly radiation
BIO22	Lowest weekly radiation
BIO23	Radiation seasonality
BIO24	Radiation of wettest quarter
BIO25	Radiation of driest quarter
BIO26	Radiation of warmest quarter
BIO27	Radiation of coldest quarter

southwestern Afghanistan and in Balochistan Province, northwestern Pakistan. The constructed MAXENT model described precisely the distribution data as the average AUC for test data was 0.972 demonstrating very good performance (with dispersion 0.003).

Summer and winter precipitation as well as the highest weekly radiation were the variables with the highest contribution to the model (Table 3). The model indicated that central and eastern regions of Zagros Mountains within territories of Fars, Kerman and western Isfahan provinces in Iran as well as in southern Khorasan Province are the most suitable regions for *P. microlepis* in Iran. The model also showed fragmented distribution range for this species; another cluster of the most suitable regions of *P. microlepis* is revealed in the bordering mountain areas of Afghanistan and Pakistan. According to the predictive map, more northern regions of Iran, Afghanistan and adjacent regions of Turkmenistan and Tajikistan are unsuitable for *P. microlepis* (Figure 1). The variables with highest values include: 1) precipitation of warmest quarter (mm); 2) precipitation of coldest quarter (mm); 3) highest weekly radiation (W m²); 4) temperature seasonality (C of V); 5) precipitation of driest week (mm); 6) radiation of driest quarter (W m²); 7) mean diurnal temperature range (mean.period max-min) (ºC) (Table 3).

4. Discussion

Paralaudakia microlepis was one of the most poorly studied species of *Paralaudakia* genus in the past. It

Table 2 All coordinate data for *Paralaudakia microlepis* for its entire distribution used in this study.

No.	Locality	Latitude	Longitude
1	Iran, Khorasan Razavi, 16 km SW Robat Sefid on the road from Mashhad to Torbat-e Heydariyeh	35.6842	59.2408
2	Iran, Fars, 180 km N Shiraz on the road to Esfahan	30.6333	53.2167
3	Iran, South Khorasan, 12 km NW Ghaen	33.8167	59.1167
4	Iran, South Khorasan, 22 km N of Birjand	33.05	59.3167
5	Iran, South Khorasan, 7 km of Khezri Dashte Biyaz	34.0833	58.8333
6	Iran, Kerman, Bab-e Maran on the road from Drab-e Behesht to Jiroft	29.0975	57.5487
7	Iran, Fars, Pole Abgine on the road from Kazeroon to Shiraz	29.5476	51.7686
8	Iran, South Khorasan, 13 km S of Zohan Zirkouh region	33.3076	59.7878
9	Iran, Fars, Sepidan on the road from Shiraz to Yasuj	30.3323	51.9622
10	Balochistan, Jaffarabad District, 6900 ft	28.5692	67.6994
11	Balochistan, Sibi Distrct, Zarghoon Valley, Shahban, 6750 ft	30.319	67.3665
12	Balochistan, Kalat District, Harboi Hills, 8640 ft	28.9927	66.7523
13	Balochistan, Killa Saifullah District, Khaisor valley, 6615 ft	31.2474	68.937
14	Balochistan, Killa Saifullah District, Toba Kakar, 7319 ft	31.2674	67.8302
15	Iran, Khorasan Province, near Birjand, Sedeh, 1700 m	33.3667	59.2
16	Iran, Kohkilueh, 15 km S Yasui, h=1895	33.5833	51.6
17	Iran, Khorasan Province, 50 km E Berjand	32.9667	59.9
18	Balochistan, Killa Saifullah, Tanishpa (Torga valley), 8050 ft	31.1683	68.4342
19	Balochistan, Killa Saifullah District, Ashewat, 6900 ft	31.3406	68.5172
20	Balochistan, Sherani District,Shinghar, 8345 ft	31.4864	69.7243
21	Balochstan, Ziarat District, Khalifat, 10 080 ft	30.3194	67.7259
22	Balochistan, Ziarat District, Malikat, 9150 ft	30.3331	67.7136
23	Iran, Kerman Province, west side of Sirch Tunnel on the road from the Kerman-Mahan road to Shahdad, elevation 8990 ft	30.157	57.4038
24	Iran, Yazd Province, north side of Shir Kuh, Dehbala, elevation 9050 ft	31.5685	54.1217
25	Iran, Kerman Province approx. 15 km SW of Rayin, north side of Kuh-e-Hezar, elevation 9125 ft	29.5519	57.2976
26	Iran, 8 km S of Robat-e Sang (27 km S of Asadabad) on rd to Torbat-e Heydariyeh	35.4833	59.2
27	Afghanistan, Ghazni Province, 21 km N of Ghazni (by Kabul Rd)	33.7017	68.495
28	Iran, Iran and Baluchistan Province, 11 km W (by road) Bazman, Al Maff, elevation 1100 m	27.8763	68.495
29	Iran, Kerman, 5 km SE Bab Maran, on the road from Darb-e Behesht to Jiroft	29.0847	57.57
30	Iran, Kerman, 3.5 km S of Lalehzar village on the road from Bardsir to Rabor	29.4908	56.8128
31	Iran, Chahal Mahal Province near Chelgerd, Kurang village, h=2385	32.5667	50.2
32	231 km N Iransahr (47 km S Khash)	28.05	60.9333
33	10 km SW Rud-e Hirmand, abandoned village SE of road from Zabol to Dust-e Mohammad Khan, 450 m	31.05	61.6333

Table 3 Relative importance of variables included in the best model.

Description of parameter	Percentage contribution
Precipitation of warmest quarter (mm)	25.2
Precipitation of coldest quarter (mm)	18
Highest weekly radiation (W m^{-2})	12.6
Temperature seasonality (C of V)	10.7
Precipitation of driest week (mm)	7.8
Radiation of driest quarter (W m^{-2})	6.1
Mean diurnal temperature range (mean(period max-min)) (°C)	5.5

was described in 1874 by Blanford from southern Iran, north of Shiraz. The model results confirm the known distribution pattern of this species. According to the model the suitability is highest in central and eastern regions of Zagros Mountains within territories of Fars and Kerman provinces as well as in southern Khorasan Province in Iran and in the bordering mountain area of Afghanistan and Pakistan. Thus the distribution of *P. microlepis* in Iran is practically limited by the mountains of the Iranian Plateau. Most of the northern mountains of Iran and the area between Iran and Afghanistan seem to be unsuitable for *P. microlepis*. The model however identified potentially suitable regions outside the known range of *P. microlepis* in the north-west of Iran and much expanded distribution range within Afghanistan where only one reliable record is registered before.

According to Anderson (1968, 1999) the habitat of this species is similar to that of *P. caucasia* but niche differences between them are still not determined. Anderson was the first who considered the problem of sympatry of mountain rock agamids in Iran. The map of potential distribution of both related species *P. microlepis* and *P. caucasia* with zones of sympatry in the north of Iran was constructed on the base of MAXENT model in this paper. It confirmed that within the Iranian Plateau

P. microlepis extends across its entire northern border to Afghanistan. *P. microlepis* distribution range overlaps with that of *P. caucasia* except in the mountains of northern extremes of its range (Anderson, 1968). The potential suitable region of sympatry is shown in the Figure 1.

We made an attempt to apply models based on those factors for several species of Asian rock agamas of genus *Paralaudakia* (*P. caucasia*, *P. microlepis*, *P. lehmanni*) for estimation of bioclimatic variables role in their distribution (Table 4). The water availability is shown as one of the most important variable for all three studied species of the genus *Paralaudakia* (Table 4). Winter precipitation is the variable with the highest contribution to the model for *P. caucasia* and *P. lehmanni* as they showed the highest average percent contribution; this variable has a second high value for *P. microlepis*. The water availability is associated with relative aridity which is of value for speciation trends of these Palearctic agamid lizards (Ananjeva and Tuniyev, 1994). We can also suppose the influence of the water availability to vegetation and its association to partial phytophagous mode of feeding. In general, the highest contribution to distribution modeling of all three studied species of genus *Paralaudakia* make the precipitation of warmest quarter, precipitation of coldest quarter, maximum temperature and solar radiation. The variables of lower contribution to distribution modeling are different in these species: radiation of driest quarter and mean diurnal temperature range for *P. microlepis* and *P. lehmanni*; minimum temperature for *P. caucasia* having more northern distribution.

For both species of *P. caucasia*-complex the relative importance of winter and summer precipitation is high as well as solar radiation. Temperature factors are also significant for these thermophilous rock agamas: for *P. caucasia* - maximal and minimal temperatures and for *P. microlepis* - temperature seasonality.

Data obtained are valuable in the light of consideration about phylogenetic relations of these both species. Baig (1992) has extended the range of *P. microlepis* by including some localities in western and several places together with *P. caucasia*, and south-western Turkmenistan. This conclusion was based on the statement (Baig, 1992; Baig *et al.*, 2012) that populations from Turkmenistan described as *P. caucasia triannulata* (Ananjeva et Atayev, 1984) should be included in *P. microlepis*. We must remind however that study of phylogenetic relationships within the *Paralaudakia caucasia* species group on the Iranian Plateau (Macey *et al.*, 1998, 2000) not only recognized *P. microlepis* and *P. caucasia* as different evolutionary lines but also placed *P. c. triannulata* within *P. c. caucasia* and demonstrated that only four nucleotide substitutions occur between *P. c. triannulata* (Caspian Sea floodplain) and the nearest *P. c. caucasia* population (Temen Spring in the western Kopet-

Table 4 Relative importance of variables used in Maxent model for 3 species of *Paralaudakia* genus.

	Description of variables	Species of genus *Paralaudakia*		
BIO1	Annual average temperature	*P. caucasia*	*P. microlepis*	*P. lehmanni*
BIO2	Annual daily temperature difference (minimal temperature– maximal temperature		5.5	4.4
BIO3	Isothermal parameter ((BIO2/BIO7) *100)		0.1	0
BIO4	Temperature seasonality (standard deviation * 100)		10.7	0
BIO5	Maximum temperature of the warmest month of the year	20.9	0.8	0
BIO6	Minimum temperature of the coldest month of the year	9.6	4	2.4
BIO7	Annual temperature scale (BIO5–BIO6)			6.1
BIO8	Average temperature of the wettest quarter of the year		4.2	6.5
BIO9	Average temperature of the driest quarter of the year		2.1	15.7
BIO10	Average temperature of the warmest quarter of the year			0
BIO11	Average temperature of the coldest quarter of the year			2.1
BIO12	Average annual precipitation		1	4.8
BIO13	Precipitation of the wettest month of the year			0.1
BIO14	Precipitation of the driest month of the year		7.8	7.7
BIO15	Seasonality of precipitation (coefficient of variation)		0.3	1.4
BIO16	Precipitation of the wettest quarter of the year			0.1
BIO17	Precipitation of the driest quarter of the year			7.7
BIO18	Precipitation of the warmest quarter of the year	18.2	25.2	6
BIO19	Precipitation of the coldest quarter of the year	34.6	18	38.9
BIO21	The highest weekly radiation	11.7	12.6	
BIO25	Radiation of the driest quarter of the year		6.1	

Dagh). Thus MAXENT data (Figure 1) show that there is a narrow zone of range's overlapping in the north of Iran.

The problem of sympatry of related species from the same complex of *Paraludakia* is correlated with ideas on hybridization and hybridogeneous origin of some forms of mountain agamas. Panov *et al.* (1987) expressed interesting hypothesis for hybridogeneous origin of the western group of populations of *P. caucasia* in Turkmenistan. They supposed that this area may be considered as the zone of secondary intergradation and some populations are a product of secondary contact between *P. caucasia* and *P. microlepis* because they exhibit hybrid characteristics. Two hypotheses are discussed in this context: a) these populations are a result of *L. caucasia* and *L. c. triannulata* hybridization, or b) these populations and also "*triannulata*" form are a result of hybridization of *L. caucasia* and *L. microlepis*. The future nuclear genome molecular study of these agamas will allow clarifying if *triannulata* populations are of hybridogeneous origin or not. The data on distribution of both species show a real and potential zone of secondary intergradation of *L. caucasia* and *L. microlepis.*

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